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LAMPAT: A Software Tool for Analyzing and Designing Thick Laminated Composite Structures

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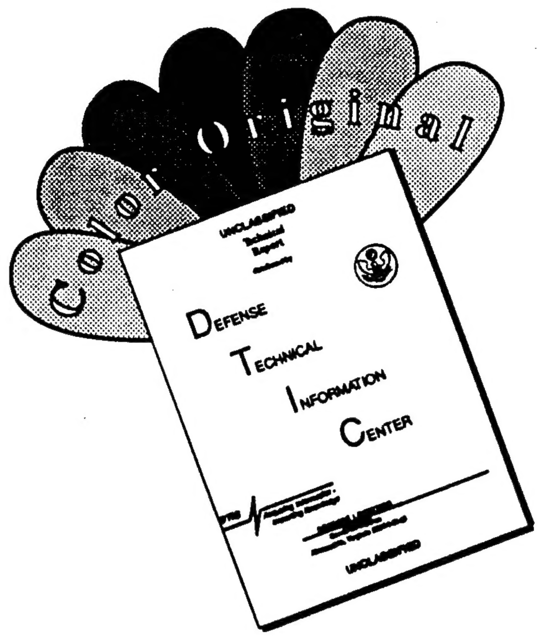

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13. ABSTRACT *(Maximum 200 words)*

The U.S. Army Research Laboratory has recently developed an innovative analysis and design software tool for evaluating the mechanical performance of thick section laminated composite material structures. The software tool has been given the name LAMPAT and is intended to be used in conjunction with traditional finite element analysis codes. LAMPAT implements a "smearing-unsmearing" methodology, an approach that is often employed in the structural analysis of thick multi-ply laminated composite structures [Chou, Carleone, and Hsu 1972]. As a pre-processing tool, LAMPAT is used to generate the effective, homogeneous, three-dimensional properties of a laminated medium for input into traditional finite element structural models. As a post-processing tool, LAMPAT is used to conduct a detailed, ply-level-based failure assessment of the structure. Results are uniquely organized in such a manner that when portrayed graphically, enable one to clearly visualize the critically loaded regions within a structure and identify the specific failure modes of concern. Failure assessment information, which can be based on a wide variety of lamina failure criteria, includes contour plots of (1) safety factor, (2) critical ply identification, and (3) the specific mode of ply failure. In this report, the theoretical basis for LAMPAT is reviewed, and illustrative examples are presented to demonstrate the utility of the software. This report is also intended to serve as a user manual for the software. LAMPAT represents a computationally efficient engineering design tool which greatly simplifies the three-dimensional failure assessment of thick section multi-layer composite structures.

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LAMPAT: A SOFTWARE TOOL FOR ANALYZING AND DESIGNING THICK LAMINATED COMPOSITE STRUCTURES

1. INTRODUCTION

The stress analyses of thick section structural components of arbitrary geometry are generally conducted within the framework of some type of numerical modeling technique (e.g., the finite element or boundary integral methods). The arbitrary nature of part geometry and boundary conditions encountered in the analysis of realistic structural components necessitates such an approach. Accurate stress and strain predictions are critical since they are often the basis upon which important design decisions are made. The heterogeneity of laminated composite structures and their inherent anisotropic properties make composites more difficult to analyze than traditional isotropic materials. The analysis of laminated composite structures is further complicated by the increased propensity for severe stress gradients to develop within anisotropic materials. Failure prediction of laminated composite structures must be based on the state of stress and strain within the constituent lamina or plies. It is therefore necessary to compute, with reasonable accuracy, the ply level (i.e., ply by ply) stress and strain states throughout the laminated composite structure before any failure criterion is implemented, upon which design decisions may be based.

Ply-by-ply stress and strain calculations may be pursued through two distinctly different approaches. One obvious approach is to treat the entire composite structure as a heterogeneous continuum, modeling each individual ply as a discrete material. Experience has shown that several finite elements through the thickness of a single ply are typically required to achieve accurate results. For thick, multi-layered composite structures (e.g., several hundred plies) this approach may not be realistic because of computational limitations. In addition, ply-by-ply analyses are extremely time consuming because of the inordinate amount of bookkeeping associated with model generation (pre-processing) and interpretation of the ply-by-ply stress and strain results (post-processing). This increases the potential for careless modeling errors. Even though the ply-by-ply analysis is perhaps the most accurate, the time investment of this approach does not always prove to be cost effective from an engineering design standpoint.

To circumvent the difficulties associated with the detailed ply-by-ply analysis, a "smearing-unsmearing" approach is often employed (see Figure 1). A representative sublaminate configuration for the composite structure is first identified (see Step 1 in Figure 1). A set of equivalent or effective homogeneous properties for this representative sublaminate configuration

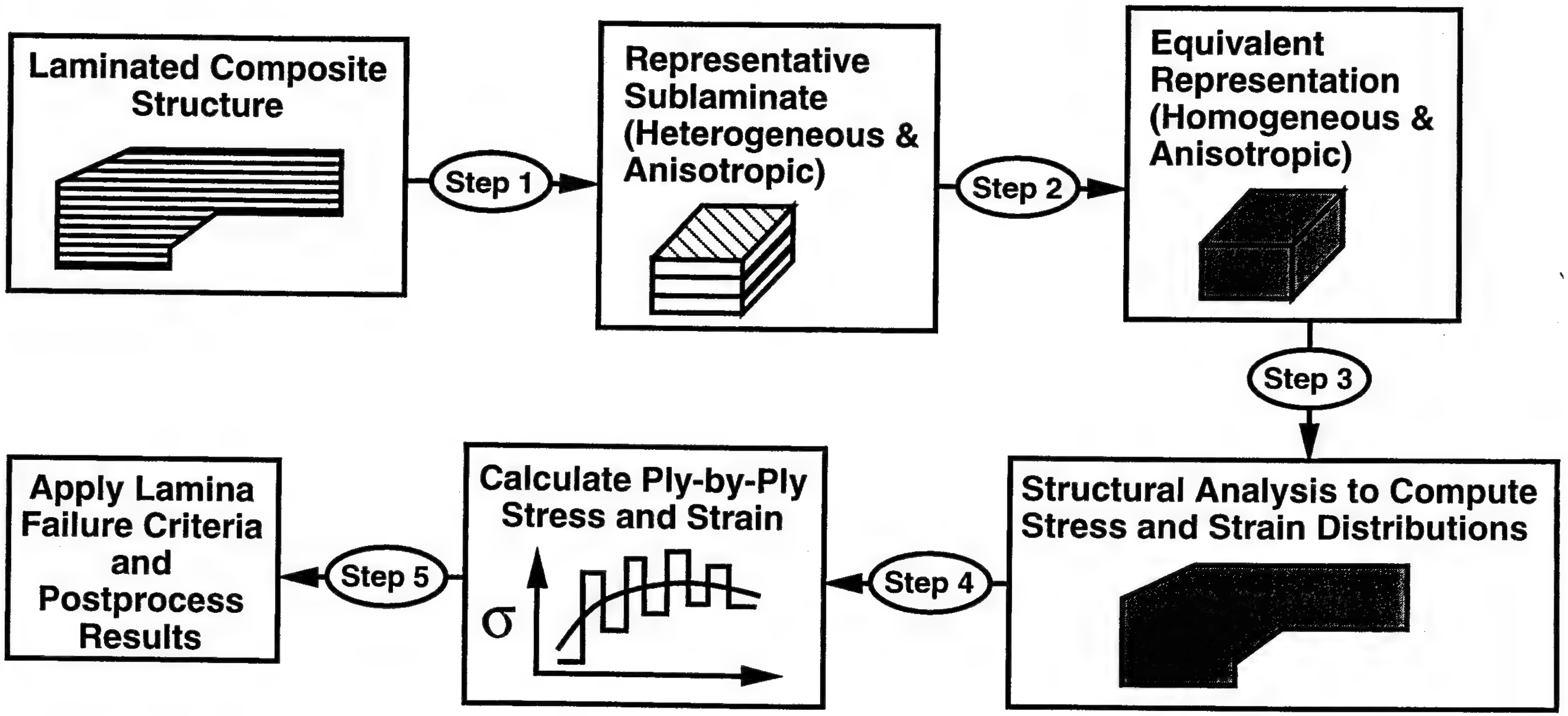

Figure 1. Smearing-unsmearing analysis methodology.

is then computed (see Step 2 in Figure 1). This step is referred to as the "smearing" of the properties. Although this is typically done with an analytical solution technique, a numerical approach may also be employed. Next, the assumption is made that a set of effective homogeneous thermo-mechanical properties of the representative sublaminate configuration can be used to replace the actual heterogeneity of the laminated material in the structural analysis. A typical structural analysis is then conducted, employing the effective thermo-mechanical properties as input, to obtain the average stress and strain distributions within the structure under the prescribe loading (see Step 3 in Figure 1). It is important to note that the stress and strain distributions here represent the average values (e.g., smooth and continuous) since the laminated material has been replaced with an equivalent set of homogeneous properties. The global stresses and strains do not reflect the actual stress and strain distributions on the ply level that are associated with the heterogeneity of the material. The ply-by-ply stress and strain states are required, however, to accurately assess failure within the structure.

At any local region or point within the structure, the ply-by-ply stress and strains can be obtained by solving the laminated media problem with the average stress and/or strain values being applied as local boundary conditions onto the representative sublaminate configuration (see Step 4 in Figure 1). This step is referred to as the "unsmearing" of the laminate stress and strains. Once the ply-by-ply stress and strain states are determined, an appropriate ply level failure criterion can be applied to assess failure (see Step 5 in Figure 1). This procedure can be employed to predict ply-by-ply stress and strain states at key local regions or points of interest within the structure (i.e., regions that are critically stressed). In the LAMPAT code, this procedure is used throughout the entire structure (i.e., for every element), ultimately providing structural performance or safety margin contour plots. In contrast to many commercially available composite analysis software codes, the LAMPAT analysis is conducted in three-dimensional space. By evaluating the three-dimensional ply stress and strain levels local to each element within a structure, the risk of overlooking non-obvious regions for potential failure is minimized. Automating this type of data reduction greatly enhances the efficiency at which thick laminated composite structures can be structurally analyzed and designed.

Note. The "smearing-unsmearing" analysis methodology does have its limitations. For example, the assumption that the material within the structure can be "homogenized" must hold true. This condition is usually satisfied in thick laminated structures where a repeating sublaminate configuration can be identified. The approach, however, does not account for bending stiffness behavior on the material level, a phenomenon typically encountered in the analysis of laminated composite plates or shells. In addition, the methodology will not predict or

capture the mechanisms associated with interlaminar shear stresses caused by discontinuous ply layers at a free edge. Although the "smearing-unsmearing" methodology is not without its limitations, its widespread use and effectiveness as a practical engineering design tool for thick laminated composite structures provides the primary motivation for this work.

In the following sections, the theoretical basis of the smearing-unsmearing methodology employed in the LAMPAT code is presented. Two illustrative examples are then presented to demonstrate the practical usefulness of the code for conducting failure assessment in thick section composite structures.

2. THEORETICAL FORMULATION

2.1 Effective Laminate Properties

Numerous models exist for predicting the effective "smeared" mechanical properties of an N layered laminate (or laminated media). The particular model presented by Chou, Carleone, and Hsu [1972] was selected for implementation in the LAMPAT code, and only the most significant features of the theory are reviewed here.

In deriving the effective "smeared" mechanical properties of an N layered laminate, an appropriate sublaminate configuration is first identified, which is considered to be representative of a "small element" (i.e., material point) within the larger structural body. A single constitutive relationship that can be used to define the effective stress/strain response of the laminate is sought. The following expression is used to represent the effective stress/strain constitutive relationship for the laminate:

$$\bar{\sigma}_i^* = \bar{C}_{ij}^* \, \bar{\varepsilon}_j^* \quad \text{for } (i, j = 1, 2, 3, 4, 5, 6) \tag{1}$$

The superscript "*" is used here to denote the "average" or effective stress and strain quantities for the laminate.

In-plane ply strains are assumed to be uniform (i.e., constant within each ply) and equal to the effective strains of the entire laminate. Mathematically, this is expressed as

$$\bar{\varepsilon}_i^k = \bar{\varepsilon}_i^* \quad \text{for } (i = 1, 2, 6; k = 1, 2, \ldots, N) \tag{2}$$

in which $_i{}^k$ represents the strain in the k^{th} ply of the laminate.

To ensure stress continuity across ply interfaces, all ply stress components associated with the out-of-plane direction are assumed to be uniform and equal to the corresponding effective stresses in the laminate. Mathematically, this is expressed as

$$\bar{\sigma}_i{}^k = \bar{\sigma}_i{}^* \text{ for } (i = 3, 4, 5; k = 1, 2, ..., N) \tag{3}$$

in which $\bar{\sigma}_i{}^k$ represents the stress in the k^{th} ply of the laminate.

All remaining effective laminate stresses and strains are assumed to be the volume average of all their corresponding ply stress and strain components, respectively. Mathematically, these assumptions are expressed as

$$\bar{\varepsilon}_i{}^* = \sum_{k=1}^{N} V^k \, \bar{\varepsilon}_j{}^k \text{ for } (i = 3, 4, 5) \tag{4}$$

$$\bar{\sigma}_i{}^* = \sum_{k=1}^{N} V^k \, \bar{\sigma}_j{}^k \text{ for } (i = 1, 2, 6) \tag{5}$$

in which V^k is the ratio of the original (i.e., undeformed) volume of the k^{th} ply over the original volume of the entire laminate.

Hooke's Law can be written for each lamina in the laminate as

$$\bar{\sigma}_i{}^k = \bar{C}_{ij}{}^k \, \bar{\varepsilon}_j{}^k \text{ for } (i, j = 1, 2, 3, 4, 5, 6; k=1,2, ..., N) \tag{6}$$

Equations (1) through (6) represent 12N+6 linear algebraic equations in 12N+12 unknowns. The following solution to equations (1) through (6) for the effective laminate stiffness matrix, $\bar{C}_{ij}{}^*$, has been derived and can be used as an equivalent (i.e., homogeneous) representation for the laminated media [Chou et al. 1972].

$$\bar{C}_{ij}^* = \sum_{k=1}^{N} V^k \left[\bar{C}_{ij}^k - \frac{\bar{C}_{13}^k \bar{C}_{3j}^k}{\bar{C}_{33}^k} + \frac{\bar{C}_{i3}^k \sum_{l=1}^{N} \dfrac{V^l \bar{C}_{3j}^k}{\bar{C}_{33}^k}}{\bar{C}_{33}^k \sum_{l=1}^{N} \dfrac{V^l}{\bar{C}_{33}^k}} \right] \text{ for } (i, j = 1, 2, 3, 6) \tag{7}$$

$$\bar{C}_{ij}^* = \bar{C}_{ji}^* = 0 \text{ for } (i = 1, 2, 3, 6; j = 4, 5) \tag{8}$$

and

$$\bar{C}_{ij}^* = \left[\frac{\sum_{k=1}^{N} \dfrac{V^k}{\Delta_k} \bar{C}_{ij}^k}{\sum_{k=1}^{N} \sum_{l=1}^{N} \dfrac{V^k V^l}{\Delta_k \Delta_l} (\bar{C}_{44}^k \bar{C}_{55}^k - \bar{C}_{45}^k \bar{C}_{54}^k)} \right] \text{ for } (i, j = 4, 5) \tag{9}$$

in which

$$\Delta_k = \begin{vmatrix} \bar{C}_{44}^k & \bar{C}_{45}^k \\ \bar{C}_{54}^k & \bar{C}_{55}^k \end{vmatrix} = \bar{C}_{44}^k \bar{C}_{55}^k - \bar{C}_{45}^k \bar{C}_{54}^k \tag{10}$$

The complete effective stress/strain constitutive relation for the laminated media is therefore given by Equations (1), (7), (8), (9), and (10). If it is more convenient to input material property data into the structural model in the form of the typical mechanical engineering property set (i.e., E_x, E_y, E_z, n_{xz}, n_{yz}, n_{xy}, G_{xz}, G_{yz}, G_{xy}), these constants can be developed straight-forwardly from Equations (7) through (10). See the derivation presented in Bogetti, Hoppel, and Drysdale [1995]. Depending on the required material property input format, LAMPAT will generate either the effective laminate stiffness matrix, $\bar{C}_{ij}^*$, or the effective mechanical engineering property set.

2.2 Ply-by-Ply Stress and Strain Determination

Ply level stress and strain values within the laminate are required for accurate failure assessment. The following section describes their determination. The assumption here is that the applied mechanical loading on the laminate or laminated media ($\bar{\sigma}_i^*$) is known and uniform and

represents the "average" or "effective" stress acting on the sub-laminate configuration. (This applied mechanical loading or stress would be determined from the finite element solution. During the LAMPAT failure assessment, this ply level stress and strain determination is conducted for each element within the structure.)

The associated "effective" or "smeared" laminate strains ($\bar{\varepsilon}_i^*$) can be obtained explicitly from the inverse relation of Equation (1). From the assumption made in Equation (2), all in-plane strain values for plies 1 through N are therefore known. Similarly, from the assumption made in Equation (3), all out-of-plane stresses for plies 1 through N are known. The out-of-plane ply strains and in-plane ply stresses remain to be determined.

The following expression for determination of the remaining out-of plane ply strains has been given explicitly by Sun and Liao [1990]

$$\begin{bmatrix} \bar{\varepsilon}_3{}^k \\ \bar{\varepsilon}_4{}^k \\ \bar{\varepsilon}_5{}^k \end{bmatrix} = \begin{bmatrix} \bar{C}_{33}{}^k & \bar{C}_{34}{}^k & \bar{C}_{35}{}^k \\ \bar{C}_{43}{}^k & \bar{C}_{44}{}^k & \bar{C}_{45}{}^k \\ \bar{C}_{53}{}^k & \bar{C}_{54}{}^k & \bar{C}_{55}{}^k \end{bmatrix}^{-1} \left[\begin{bmatrix} \bar{\sigma}_3{}^k \\ \bar{\sigma}_4{}^k \\ \bar{\sigma}_5{}^k \end{bmatrix} - \begin{bmatrix} \bar{C}_{31}{}^k & \bar{C}_{32}{}^k & \bar{C}_{36}{}^k \\ \bar{C}_{41}{}^k & \bar{C}_{42}{}^k & \bar{C}_{46}{}^k \\ \bar{C}_{51}{}^k & \bar{C}_{52}{}^k & \bar{C}_{56}{}^k \end{bmatrix} \begin{bmatrix} \bar{\varepsilon}_1{}^k \\ \bar{\varepsilon}_2{}^k \\ \bar{\varepsilon}_6{}^k \end{bmatrix} \right] \tag{11}$$

Since all the ply strains are now known, the remaining undetermined in-plane ply stresses can be calculated through the following relation:

$$\begin{bmatrix} \bar{\sigma}_1{}^k \\ \bar{\sigma}_2{}^k \\ \bar{\sigma}_6{}^k \end{bmatrix} = \begin{bmatrix} \bar{C}_{11}{}^k & \bar{C}_{12}{}^k & \bar{C}_{13}{}^k & \bar{C}_{14}{}^k & \bar{C}_{15}{}^k & \bar{C}_{16}{}^k \\ \bar{C}_{21}{}^k & \bar{C}_{22}{}^k & \bar{C}_{23}{}^k & \bar{C}_{24}{}^k & \bar{C}_{25}{}^k & \bar{C}_{26}{}^k \\ \bar{C}_{61}{}^k & \bar{C}_{62}{}^k & \bar{C}_{63}{}^k & \bar{C}_{64}{}^k & \bar{C}_{65}{}^k & \bar{C}_{66}{}^k \end{bmatrix} \begin{bmatrix} \bar{\varepsilon}_1{}^k \\ \bar{\varepsilon}_2{}^k \\ \bar{\varepsilon}_3{}^k \\ \bar{\varepsilon}_4{}^k \\ \bar{\varepsilon}_5{}^k \\ \bar{\varepsilon}_6{}^k \end{bmatrix} \tag{12}$$

2.3 Failure Assessment Summary

The failure assessment of a single ply or lamina is generally based on both the magnitude of the ply level stress (or strain) state and a particular lamina failure criterion. The actual predicted strength or failure assessment of the overall laminate is defined somewhat in a more arbitrary manner. For example, for a given set of mechanical and/or thermal loads imposed on the laminate, any number of various failure modes could occur in one or more plies. A single failure (or even multiple failures) on the ply level does not generally result in catastrophic failure of the laminate. In fact, depending on the laminate stacking sequence and loading, a laminate will often undergo several minor ply level failures before catastrophic failure occurs.

The term first ply failure refers to an approach in which the overall laminate strength is determined by the lowest point of laminate load that causes any failure mode to occur in any ply within the laminate. Although this approach is common, it generally provides laminate strength predictions that are far too conservative.

A more practical and often more accurate approach is the progressive ply failure theory. In this situation, the laminate load is increased to a point when failure is first predicted in any mode within a ply within the laminate (first ply failure). This load level is noted. The corresponding lamina stiffness for that ply is then reduced to an appropriate value for the level of damage assumed and the laminate is re-loaded until the next failure is detected. (In LAMPAT, all ply stiffness is reduced to an insignificantly small value, which represents complete damage.) This allows ply level loads to redistribute within the laminate and simultaneously prevents the load from accumulating in the component directions of previously detected failure modes. The procedure of loading to failure and reducing corresponding stiffness is continued in an iterative manner until the laminate can no longer support the initially defined load. The ultimate laminate strength is defined as the largest load level reached during the loading strategy. The particular mode of failure and the actual ply that corresponds to the largest load level are referred to as the critical mode and critical ply responsible for ultimate laminate failure.

3. LAMPAT IMPLEMENTATION

3.1 Overview of Operation

LAMPAT is a user-friendly, data base-driven computer program designed to assist in the failure analysis of thick section composite structures. As the development of the LAMPAT software progresses, it is important to note that the particular LAMPAT software described in

this report is Version 3.0, hereafter referred to as LAMPAT(3.0). LAMPAT(3.0) is formatted to interface with the PATRAN analysis software package (Version 2.5) [PDA Engineering 1990] and traditional finite element programs including ANSYS (Version 4.4) [DeSalvo and Gorman 1989], ABAQUS (Version 5.2) [Hibbitt, Karlsson, and Sorensen, Inc. 1992], DYNA3D [Whiley and Engelmann 1993], and NIKE3D [Maker, Ferencz, and Hallquist 1991]. The specific element types accommodated are STIFF42 for ANSYS, CAX8X for ABAQUS, and eight noded bricks for DYNA3D. The format statements in LAMPAT(3.0) can be easily modified to interface with other finite element solver programs. Inquiries for obtaining the software should be made through one of the authors.

During the entire structural analysis process, LAMPAT(3.0) is used two times. LAMPAT(3.0) is first used as a pre-processor to generate smeared or effective laminate properties for input into the finite element model. Input for the pre-processing phase is read into LAMPAT(3.0) through a user-defined data base. LAMPAT(3.0) is then used, after the finite element solution has been completed, as a post-processor to perform a failure assessment of each element within the structure. Input for the post-processing phase includes the user-defined data base, the finite element model details, and the finite element global stress results. The failure assessment summary information generated in LAMPAT(3.0) can be viewed graphically using PATRAN analysis software [PDA Engineering 1990]. A flow chart summarizing the pre- and post-processing phases of the LAMPAT(3.0) analysis is illustrated schematically in Figure 2.

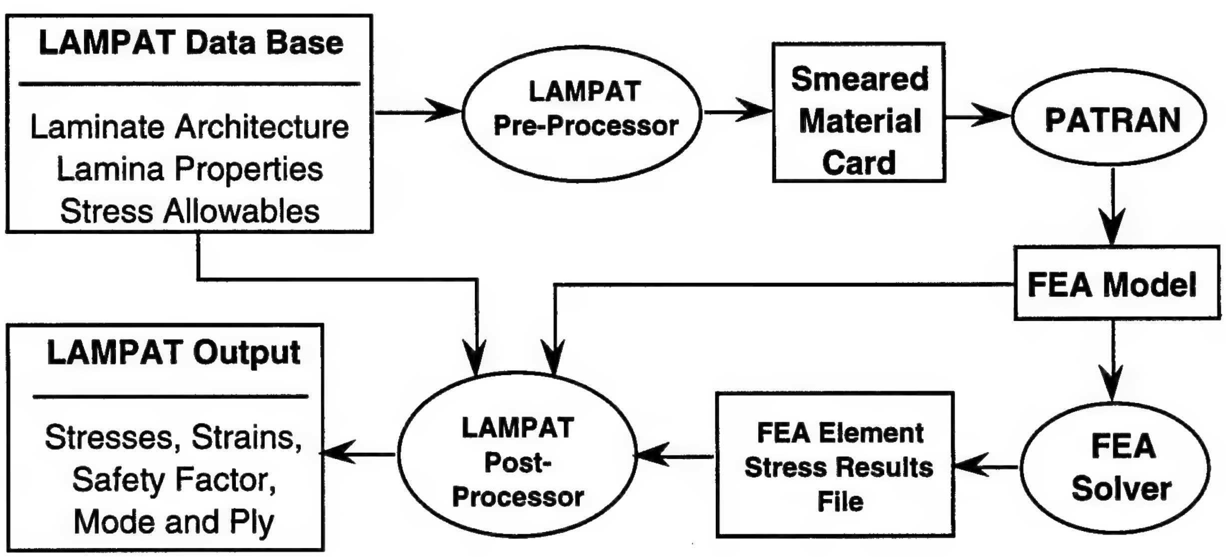

Figure 2. Flow chart of the analysis process.

3.2 User-defined Material Data Base for LAMPAT(3.0)

LAMPAT(3.0) reads information from a data base file that contains lamina properties and strength allowables for all the ply materials of interest as well as all the laminate architecture details. The sample data base presented in Appendix A will be used to illustrate the data base file format. In the data base, the data are written in "free format," in which all data are delimited by commas and spaces on each line. The exclamation point (!) is used for inserting comment statements; all the information to the left of the exclamation point is data to be input into the program; the information to the right is ignored by the program. The data base is subdivided into three sections: the first section consists of two header cards, the second section defines the various regions within the model, and the third section is essentially a "material library."

Any self-consistent set of units may be used in the LAMPAT(3.0) data base. Typically for SI units, Pascals (Pa) are used for pressure, meters (m) for length, kilograms per meter cubed for density (kg/m^3) and degrees Celsius (°C) for temperature. For English units, pounds per square inch (lb/in^2) are used for pressure, inches (in.) for length, slugs per inch cubed ($slug/in^3$) for density, and degrees Fahrenheit (°F) for temperature.

3.2.1 *Header Cards*

The first section of the data base contains two header cards. The first header card designates the number of regions to be defined in the LAMPAT(3.0) data base. The number of regions defined in the data base should correspond identically with the number of "material regions" in the PATRAN finite element model. (The term "material region" here refers to all elements in the model having the same PATRAN defined [MID] parameter. See PDA Engineering [1990] for details.) For each region, LAMPAT(3.0) creates one smeared material property data set for finite element model input. A region can consist of an isotropic material, a composite laminate, or a hybrid laminate. The second card defines the number of different materials listed in the data base. This does not have to equal the number of materials actually used in the various regions within the structure. For example, the data base shown in Appendix A has three different materials listed, but only two are actually used to define the region properties.

3.2.2 *Definition of Regions*

The second section of the data base defines all the various regions that comprise the entire finite element model. In the example data base shown in Appendix A, two regions have been defined (the first is a composite laminate and the second is solid aluminum).

The first card in each region section contains the region identification number (REG_ID), the failure criterion identification number (FAIL_CRT) and the maximum number of iterations to be performed in the progressive failure analysis (ITERS). The region identification number relates the LAMPAT(3.0) generated effective properties for a given region to the corresponding region defined in the finite element model (i.e., the corresponding PATRAN defined (MID) group of elements). The failure criterion identification number defines the particular failure criterion that will be used for the laminate failure assessment in that region. Eight different failure criteria are available in LAMPAT(3.0): (1) Von Mises-Henecky [Hertzberg 1989], (2) maximum stress [Tsai 1987], (3) maximum strain [Tsai 1987], (4) hydrostatic pressure adjusted [Hahn and Kallas 1992; Hoppel, Bogetti, and Gillespie 1995], (5) Tsai-Wu quadratic interaction [Tsai and Wu 1971], (6) Christensen's [Christensen, 1988], (7) Feng's [Feng 1991] and (8) the modified Hashin [Hashin 1980; Gipple, Nuismer, and Camponeschi 1995]. A detailed description of the failure theories is given in a separate report [Bogetti et al. 1995]. The maximum number of iterations to be performed is the number of times the program will iterate during the progressive ply failure analysis. The fourth parameter on this line is reserved to accommodate future enhancements of the LAMPAT(3.0) code and should be set to 0.0.

The second card in each region section contains the parameters BETA, PHI, and SI. These are the Euler angles (in degrees) that describe the orientation of the region's local laminate coordinate system (x', y', z') with respect to the global finite element model coordinate system (X, Y, Z). BETA defines the rotation about the x' axis, PHI defines the rotation about the y' axis, and SI defines the rotation about the z' axis. If the local laminate coordinate system is coincidental with the global coordinate system, then these three parameters should all be set equal to 0.0. An example illustrating the LAMPAT(3.0) region rotations is given in Figure 3a. The fourth parameter on this line is reserved to accommodate future enhancements in the LAMPAT(3.0) code and should be set to 0.0.

The third card in each region section defines the number of plies used to describe the laminate (NPLY) and the region type (REG_TYP). The region type should be set to 1.0 if the region will have isotropic properties or set to 2.0 if the region will have anisotropic properties.

The other two parameters on this line are reserved for future LAMPAT(3.0) enhancements and should be set to 0.0. For the current region, the following (NPLY) lines are used to define the individual plies of the laminate for the region. Each line contains four parameters, the material number (MAT_#), the ply thickness (THICKNESS), the in-plane ply orientation angle in degrees (ANGLE), and the thermal ply loading (TEMP). The material number defines the specific material to be used for the ply (selected from the numbers listed in the material library section of the data base). Note that by specifying the ply materials individually, the analysis of hybrid laminates is easily accommodated. The thickness parameter (THICKNESS) is the relative thickness of each ply in the laminate. The in-plane ply orientation angle (ANGLE) is the rotation angle of the longitudinal (1-direction) axis of the ply in the x'-y' plane of the local laminate coordinate system for that region (see Figure 3b). The thermal ply loading (TEMP) parameter defines the difference between the operating temperature and processing temperature of the ply. Thermal loadings are accounted for in the laminate failure assessment. Note that by specifying the thermal ply loading in this manner, the laminate is not restricted to a uniform thermal loading profile.

3.2.3 *Material Library*

The last section of the data base file is structured in a "material library" type format. This section contains the three-dimensional ply properties, densities, and strength parameters for all the materials included in the data base. The number of materials listed in this section should be equal to that defined in the second card of the first section. Each individual material listed in the data base file occupies 45 cards (lines), with three columns (entries) for each card. The "45 card" format for one material is described below. (Additional materials included in the data base file would be inserted in exactly the same format.)

The first card contains the material number (MAT_#), the material type (MAT_TYP), and the material density (MAT_DENS). The first material listed in the file would have an (MAT_#) of 1.0, the second 2.0, and so on. The material type parameter (MAT_TYP) is reserved to accommodate future enhancements and should always be set to 1.0. If required in the analysis, the material density (MAT_DENS) should also be specified.

Global Finite Element Model (X,Y,Z)
and
Local Laminate Coordinate Systems (x',y',z')

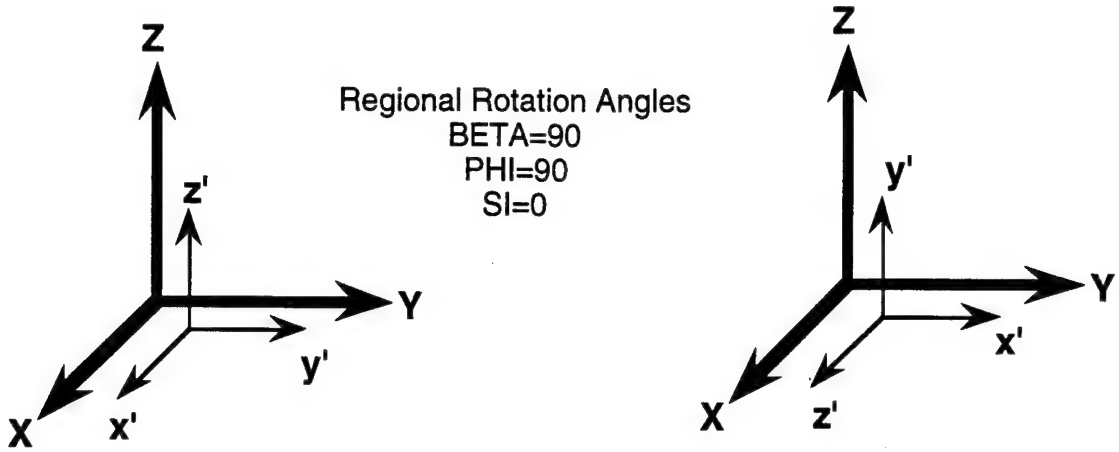

Figure 3a. Illustration of regional (local laminate coordinate system) rotation angles. (The coordinate system on the left shows the local laminate coordinate system of the region coincidental with the global finite element model coordinate system. The region rotation angles [BETA=90°, PHI=90°, and SI=0°] would define a local laminate coordinate system rotation of 90° about the x' axis and subsequent 90° rotation about the y' axis, resulting in the final orientation shown on the right.)

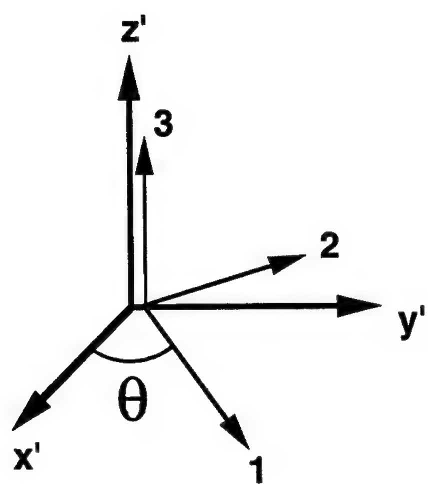

Figure 3b. Ply orientation angle, q, definition within the local laminate coordinate system.

The second card contains the elastic moduli for the ply material defined in its three principal coordinate directions (i.e., E_1, E_2, E_3). (Note that if the material is isotropic, the same value should be entered for all three moduli.) The third card contains the three major Poisson's ratios for the material (i.e., ν_{23}, ν_{13}, ν_{12}). The fourth card contains the three shear moduli for the

material (i.e., G_{23}, G_{13}, G_{12}). The fifth card contains the thermal expansion coefficients in the three principal coordinate directions (i.e., α_{11}, α_{22}, α_{33}).

Cards 6 through 45 contain all the parameters required to define the failure criteria of the material. For each failure criterion (1 through 8), the data base reserves five cards (lines), each with three columns. Since there are eight failure criteria, 40 cards are reserved for each material to define all the potentially required failure parameters. A detailed description of each of following failure criteria is discussed elsewhere in Bogetti et al. [1995].

The Von Mises-Henecky failure criterion [Hertzberg 1989] is the first one listed. The only datum the program requires for this failure criterion is the material yield strength, (σ_y), which should be listed in the first column of the first card (designated as VM1 in the sample data base file in Appendix A). Since the program does not require any additional information for this failure criterion, the remaining 14 positions may all be defined as 0.0 (see the aluminum material in the data base file in Appendix A).

The second failure criterion is the maximum stress [Tsai 1987], which requires nine constants. The constants are X1T (the ultimate tensile strength in the 1-direction), X1C (the ultimate compressive strength in the 1-direction), X2T (the ultimate tensile strength in the 2-direction), X2C (the ultimate compressive strength in the 2-direction), X3T (the ultimate tensile strength in the 3-direction), X3C (the ultimate compressive strength in the 3-direction), X23 (the ultimate shear strength in the 2-3 plane), X13 (the ultimate shear strength in the 1-3 plane), and X12 (the ultimate shear strength in the 1-2 plane).

The third failure criterion is the maximum strain [Tsai 1987], which also requires nine constants. The constants are Y1T (the ultimate tensile strain in the 1-direction), Y1C (the ultimate compressive strain in the 1-direction), Y2T (the ultimate tensile strain in the 2-direction), Y2C (the ultimate compressive strain in the 2-direction), Y3T (the ultimate tensile strain in the 3-direction), Y3C (the ultimate compressive strain in the 3-direction), Y23 (the ultimate shear strain in the 2-3 plane), Y13 (the ultimate shear strain in the 1-3 plane), and Y12 (the ultimate shear strain in the 1-2 plane).

The fourth failure criterion is the hydrostatic pressure adjusted [Hahn and Kallas 1992; Hoppel et al. 1995], which requires 15 constants. The constants are X1T (the tensile strength in the longitudinal or 1-direction); X2T (the tensile strength in the transverse or 2-and 3-directions); HPD (the hydrostatic pressure definition factor; if the hydrostatic pressure state for the ply is

assumed to be equal to the minimum of σ_2 and σ_3, HPD should be set equal to 1.0; if the hydrostatic pressure state is assumed to be equal to the average of σ_2 and σ_3, HPD should be set equal to 2.0); X1C(0) (the compressive strength in the longitudinal or 1-direction under no hydrostatic pressure); X2C(0) (the compressive strength in the transverse or 2- and 3-directions under no hydrostatic pressure); S (the shear strength for the material, assumed equal in all planes and under no hydrostatic pressure); ML1, ML2, and LTP (the primary and secondary slopes of the longitudinal compressive strength versus hydrostatic pressure relation and the transition pressure for that relation, respectively); MT1, MT2, and TTP (primary and secondary slopes of the transverse compressive strength versus pressure relation and the transition pressure for that relation, respectively); and MS1, MT2, and STP (the primary and secondary slope of the shear strength versus pressure relation and the transition pressure for that relation, respectively).

The fifth failure criterion is the Tsai-Wu [Tsai and Wu 1971], which requires the following seven parameters to be defined: X1T (the tensile strength in the 1-direction), X1C (the compressive strength in the 1-direction), X2T (the tensile strength in the 2-direction), X2C (the compressive strength in the 2-direction), S12 (the shear strength in the 1-2 plane), and F12 and F23 (experimentally determined parameters defined in Tsai and Wu [1971]).

Christensen's failure criterion [Christensen 1988] is the sixth failure criterion listed, and it requires the following 11 parameters to be defined: the typical engineering constants E_1, E_2, E_3, n_{23}, n_{13}, n_{12}, G_{23}, G_{13}, G_{12}; K and α (experimentally determined parameters); and Y1T and Y1C (the 1-direction failure strains for the lamina in tension and compression, respectively).

The seventh failure criterion is Feng's [Feng 1991], which requires the following six parameters to be defined: A_1, A_{11}, A_2, A_4, A_5 and A_{55} (all experimentally determined material parameters, defined elsewhere [Hahn and Kallas 1992]).

The eighth failure criterion, the modified Hashin's failure criterion [Hashin 1980; Gipple et al. 1995], requires the same nine parameters from the data base as the maximum stress failure criterion (X1T, X2T, X3T, X1C, X2C, X3C, X23, X13, and X12).

3.3 Pre-Processing with LAMPAT(3.0)

After the LAMPAT(3.0) data base has been created, the LAMPAT(3.0) program can be used to generate material cards containing the effective three-dimensional properties for each region in the model. LAMPAT(3.0) execution requires the user to supply input interactively.

The required input for pre-processing includes the LAMPAT(3.0) data base file and a file name for the output material property file. A sample of a typical interactive session is given in Appendix B. The specific format of the material property file generated will depend on the element type being used in the finite element analysis. For the ANSYS and ABAQUS solvers, the material file format is that of the input neutral file in PATRAN. For the DYNA3D solver, the material property file is consistent with DYNA3D input format.

3.4 Post-Processing with LAMPAT(3.0)

As a post-processing program, LAMPAT(3.0) conducts a detailed failure assessment of the structural model on an element-by-element basis. Required input for LAMPAT(3.0) post-processing includes (1) the LAMPAT(3.0) data base file, (2) the PATRAN neutral file of the model, and (3) the finite element-generated stress results file. For each element in the model, LAMPAT(3.0) "unsmears" the global finite element stresses and computes all the associated ply level stresses for the laminate architecture defined for the element. The ply level failure criterion specified in the material data base is then applied to each ply in the laminate.

For failure assessment purposes, the ultimate laminate load or laminate strength is defined in terms of a safety factor (SF), which is the ratio of the ultimate laminate load (as defined by first ply or progressive ply failure) to the applied loading. The ultimate load is a scalar multiple of the applied three-dimensional loading (i.e., the element stress state). According to this definition, safety factors less than one represent laminate failures. The critical mode of failure and the critical ply associated with the calculated safety factor are also identified in the laminate failure analysis. This is valuable information since it facilitates the redesign or optimization of laminate architectures for the given structural loading requirements.

LAMPAT(3.0) creates a failure assessment results output file with 15 columns of data for each element. The file is written into the results neutral file format of PATRAN. The first six columns are the global finite element stresses (defined in the global finite element model coordinate system), the seventh through the twelfth columns contain the six global strains (also defined in the global finite element model coordinate system), and the last three columns contain the safety factor, critical mode, and critical ply for each element in the structure, respectively.

In the results, the critical mode is reported as an integer with a value between 1 and 9 for each element. The definition of the mode number depends on the specific failure criterion that it is associated with. In regions where the Von Mises or Tsai-Wu failure criteria are used, there is

only one operative failure mode, so the mode will always be equal to 1.0. The maximum stress, maximum strain, and hydrostatic pressure-adjusted failure criteria all contain nine operative failure modes. The definitions of these modes are given in Table 1. Christensen's failure criterion has three potential failure modes, which are defined in Table 2. Both Feng's failure criteria and the modified version of Hashin's failure criteria distinguish between four distinct failure modes (see Table 3).

Table 1. Definition of Failure Modes for the Maximum Stress, Maximum Strain, and Hydrostatic Pressure-Adjusted Failure Criteria

Mode Number (MODE)	Definition
1	Tensile failure in the 1-direction (X1T)
2	Compressive failure in the 1-direction (X1C)
3	Tensile failure in the 2-direction (X2T)
4	Compressive failure in the 2-direction (X2C)
5	Tensile failure in the 3-direction (X3T)
6	Compressive failure in the 3-direction (X3C)
7	Shear failure in the 23-plane (S23)
8	Shear failure in the 13-plane (S13)
9	Shear failure in the 12-plane (S12)

Table 2. Definition of Failure Modes for Christensen's Failure Criterion

Mode Number (MODE)	Definition
1	Tensile failure in the fiber direction (X1T)
2	Compressive failure in the fiber direction (X1C)
3	Matrix Failure

The critical ply number that is reported in the LAMPAT(3.0) results file is an integer corresponding to the ply number defined in the LAMPAT(3.0) data base. For example, in the data base in Appendix A, the first region consists of four plies. If the LAMPAT(3.0) results file indicated that the critical ply was 4.0 in this region, then this would correspond to the fourth or

0° ply. A critical ply number of 3.0 would correspond to the 90° ply. In the second region, there is only one ply (solid aluminum); therefore, the critical ply will be 1.0 for this entire region.

Table 3. Definition of Failure Modes for Feng's and the Modified Version of Hashin's Failure Criteria

Mode Number (MODE)	Definition
1	Tensile failure in the fiber direction (X1T)
2	Compressive failure in the fiber direction (X1C)
3	Tensile failure in the Matrix
4	Compressive failure in the Matrix

Note that a comprehensive failure assessment of a given structure is usually made by studying the safety factor, critical mode, and critical ply results in conjunction with the assumed data base input properties and failure parameters. For example, the safety factor plot may indicate that several areas in the structure are critical (have low safety factors). For these areas, the critical mode and the critical ply plots will indicate the specific failure mode(s) and ply number(s) responsible for failure. Since composite properties and strength parameters can vary considerably, the analyst should consider the usefulness of carefully designed parametric studies to quantify the sensitivity of the failure assessment results to the specific input used in the data base.

4. EXAMPLE PROBLEMS

4.1 Filament-Wound Composite Cylinder Subject to Axial Compression

One of the structures that has been analyzed using LAMPAT(3.0) is an aluminum end cap fixture for a thick walled filament-wound graphite-epoxy composite cylinder loaded in axial compression. The composite cylinder was constructed of typical graphite fiber-reinforced epoxy material and had 50% of the plies oriented in the hoop direction and 50% of the plies oriented in the axial direction (i.e., a [0/90/90/0] lay-up). The pre-processing of the finite element model was conducted with PATRAN using two-dimensional axi-symmetrical elements as shown in Figure 4. Boundary conditions were applied to the model so that the top edge of the composite was fixed in the axial direction. A uniform pressure of 298 MPa (43.2 ksi) was applied to the bottom of

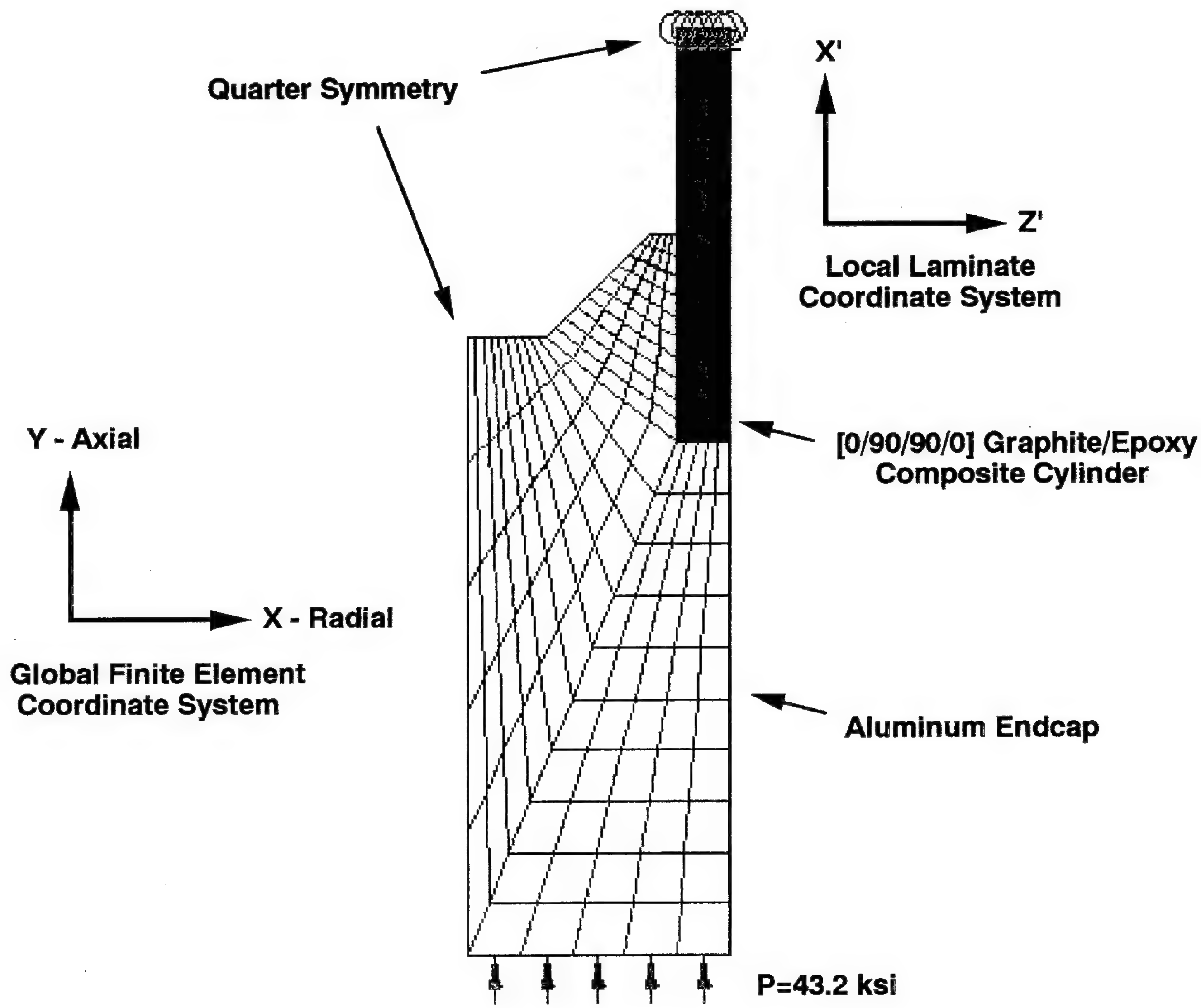

Figure 4. Axi-symmetrical finite element model of a filament-wound graphite-epoxy composite cylinder with an aluminum end cap.

the end cap. This loading results in a far field axial stress in the composite cylinder of approximately 828 MPa (120 ksi), which is near the theoretical ultimate for the laminate architecture assumed. LAMPAT(3.0) was used to create material cards for the composite laminate and aluminum regions. The data base used for this problem is shown in Appendix A. Note that the local laminate rotation angles for the composite cylinder region (region 1.0) are BETA=90°, PHI=90°, and SI=90°, and all rotation angles for the aluminum region (region 2.0) are zero.

ANSYS version 4.4 software [DeSalvo and Gorman 1989] was used to solve for the global stress distributions within the structure. LAMPAT(3.0) was used to conduct the failure assessment of the structure. The aluminum end cap was evaluated using the Von Mises failure criterion [Hertzberg 1989], assuming a material yield strength of 552 MPa (80 ksi). The composite laminate region was evaluated using the maximum stress failure criterion [Tsai 1987]. The ply-level strength allowables used for the graphite-epoxy are given in Table 4.

Table 4. Typical Graphite Fiber-Reinforced Epoxy Strength Allowables

	Strength (MPa)	Strength (ksi)
Fiber Direction Tensile Strength (X1T)	2897.0	420.0
Fiber Direction Compressive Strength (X1C)	1207.1	175.0
Transverse Tensile Strength (X2T=X3T)	60.0	8.7
Transverse Compressive Strength (X3T=X3C)	206.9	30.0
In-Plane Shear Strength (S12)	83.8	12.0
Out-of-Plane Shear Strength (S13=S23)	41.4	6.0

The results of the LAMPAT(3.0) failure assessment are shown in Figures 5, 6, and 7. Figure 5 shows a safety factor contour plot for the structure. Notice that the safety factor is lowest (slightly less than 0.615) in a small part of the composite section at the interface with the end cap. Figure 6 indicates that the critical mode of failure in this region is interlaminar shear (S13), or MODE=8. Correspondingly, Figure 7 shows that the critical ply is ply number 4, which is the [0] ply. These observations suggest that interlaminar shear failure at the composite end cap interface is a likely failure mode of concern. The indicated critical mode for the rest of the composite section is fiber compression (X1C), or MODE=2, in the [0] ply. Since the safety factors in the composite region where this fiber compression failure is indicated are also substantially less than 1, this would also be a failure mode of concern. The entire aluminum

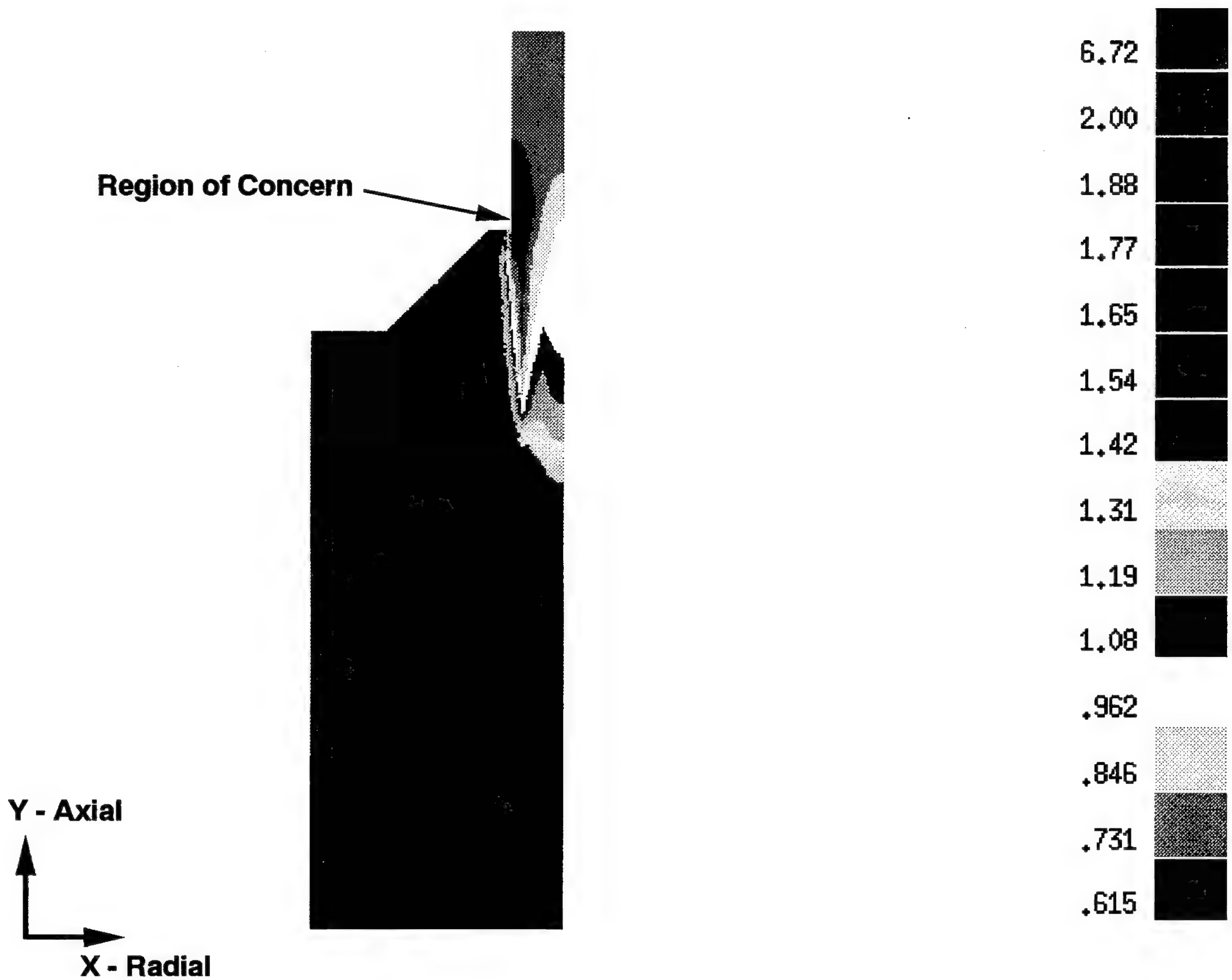

Figure 5. Safety factor contour plot.

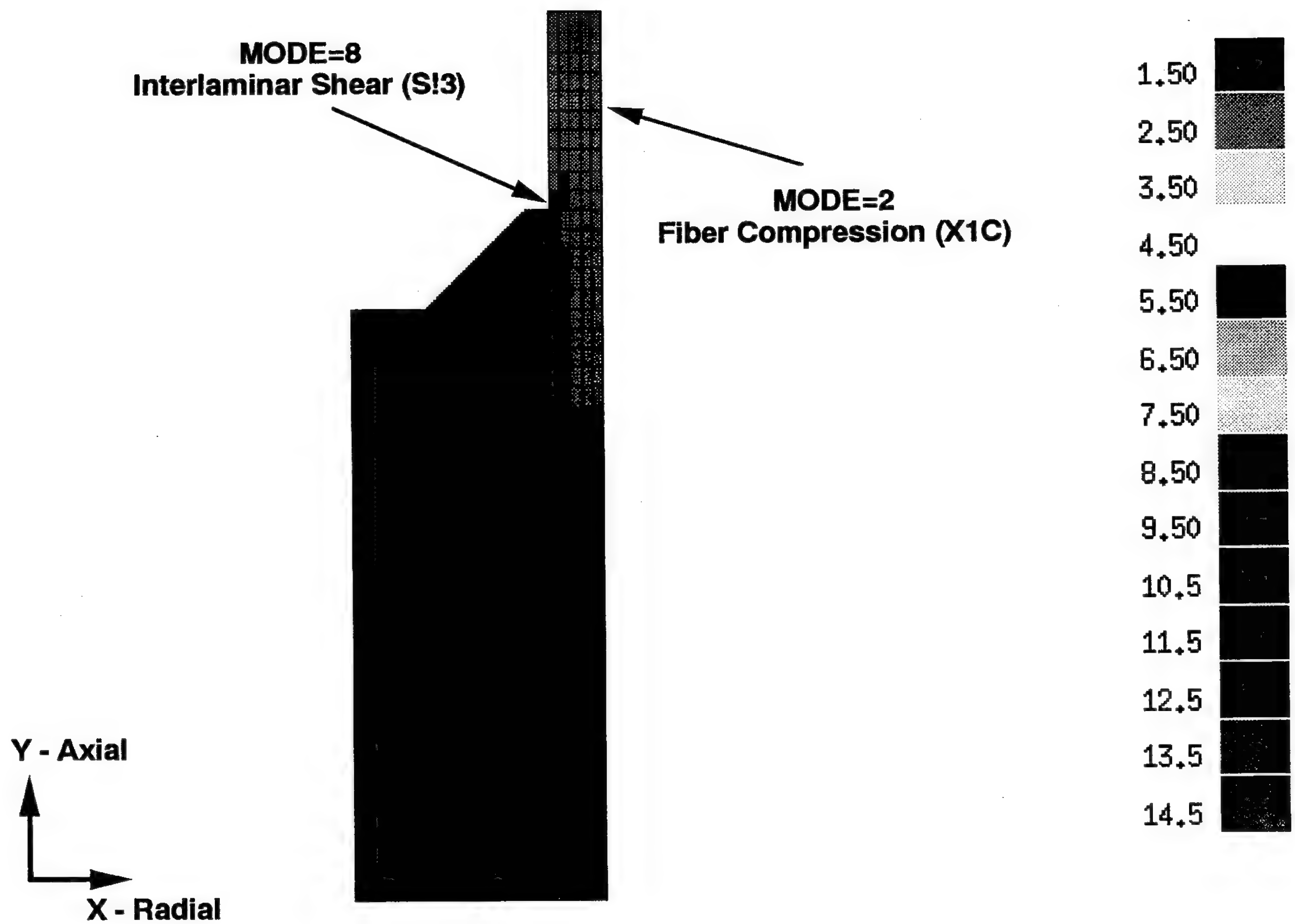

Figure 6. Critical mode identification plot.

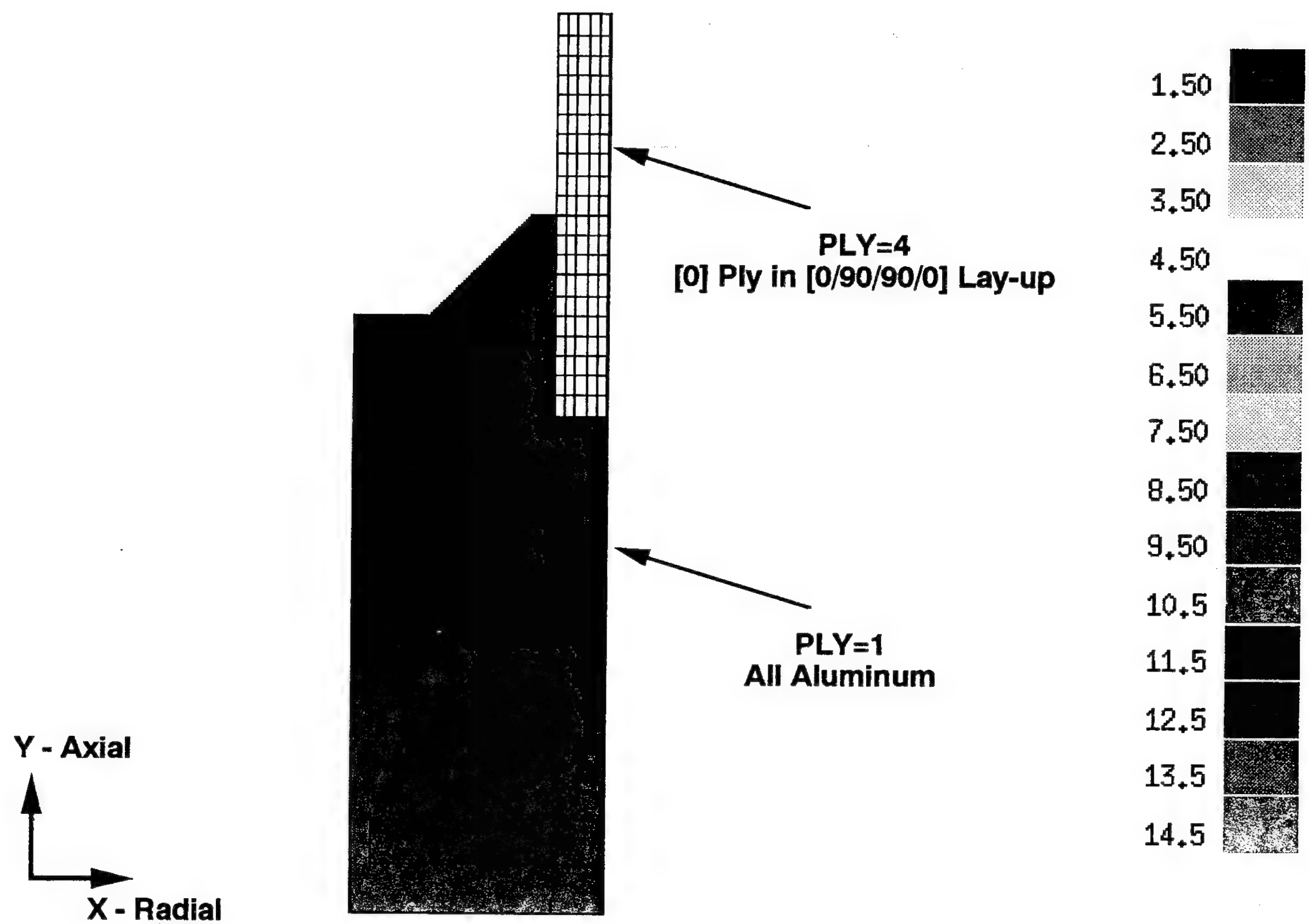

Figure 7. Critical ply identification plot.

end cap region appears to be structurally sound, as indicated by the fact that all the safety factor values within this region are greater than 1.2. Note that since the only operative failure mode considered for the aluminum is Von Mises yielding, Figure 6 indicates MODE=1, or Von Mises yielding as the failure mode for the entire end cap.

4.2 Composite Sandwich Coupon in Three-Point Bending Coupon

LAMPAT(3.0) was also used to conduct failure assessment of a composite sandwich coupon loaded in three-point bending. The coupon, as shown in Figure 8, comprised two face sheets of S2-glass fabric-reinforced polyester bonded to an aluminum honeycomb core. The S2-glass material was a plain weave fabric tow sheet (five yarns per inch) and the individual layers of the face sheets were laminated so that the entire face sheet material could be considered to behave as a homogeneous "quasi-isotropic" material (e.g., having an overall laminate stacking sequence of [0/90/+45/-45/-45/+45/90/0]). The face sheet and the aluminum honeycomb core materials were modeled as homogeneous materials requiring only one ply to represent each region but possessing directionally dependent properties. The adhesive bonding material was not included in the model. LAMPAT(3.0) was used to generate the material cards for the model. The effective material properties and strength allowables for both the face sheet and core materials used in this case study were taken from Condon and Gregory [1994] (see Tables 5 and 6 for the strength allowables used). The local laminate coordinate system for each region is oriented so that the x' direction is aligned with the span or global x finite element coordinate direction. Referring to the coordinate system definitions in Figure 8, the local laminate rotation angles for both regions are BETA=-90°, PHI=0°, and SI=0°.

Table 5. Strength Allowables for the S2-Glass Fabric-Polyester Material

	Strength (MPa)	Strength (ksi)
In-Plane Tensile Strength (X1T = X2T)	302.1	43.8
In-Plane Compressive Strength (X1C = X2C)	110.4	16.0
Through-the-thickness Tensile Strength (X3T)	24.8	3.6
Through-the-thickness Compressive Strength (X3C)	466.9	67.7
In-Plane Shear Strength (S12)	63.5	9.2
Interlaminar Shear Strength (S13=S23)	15.2	2.2

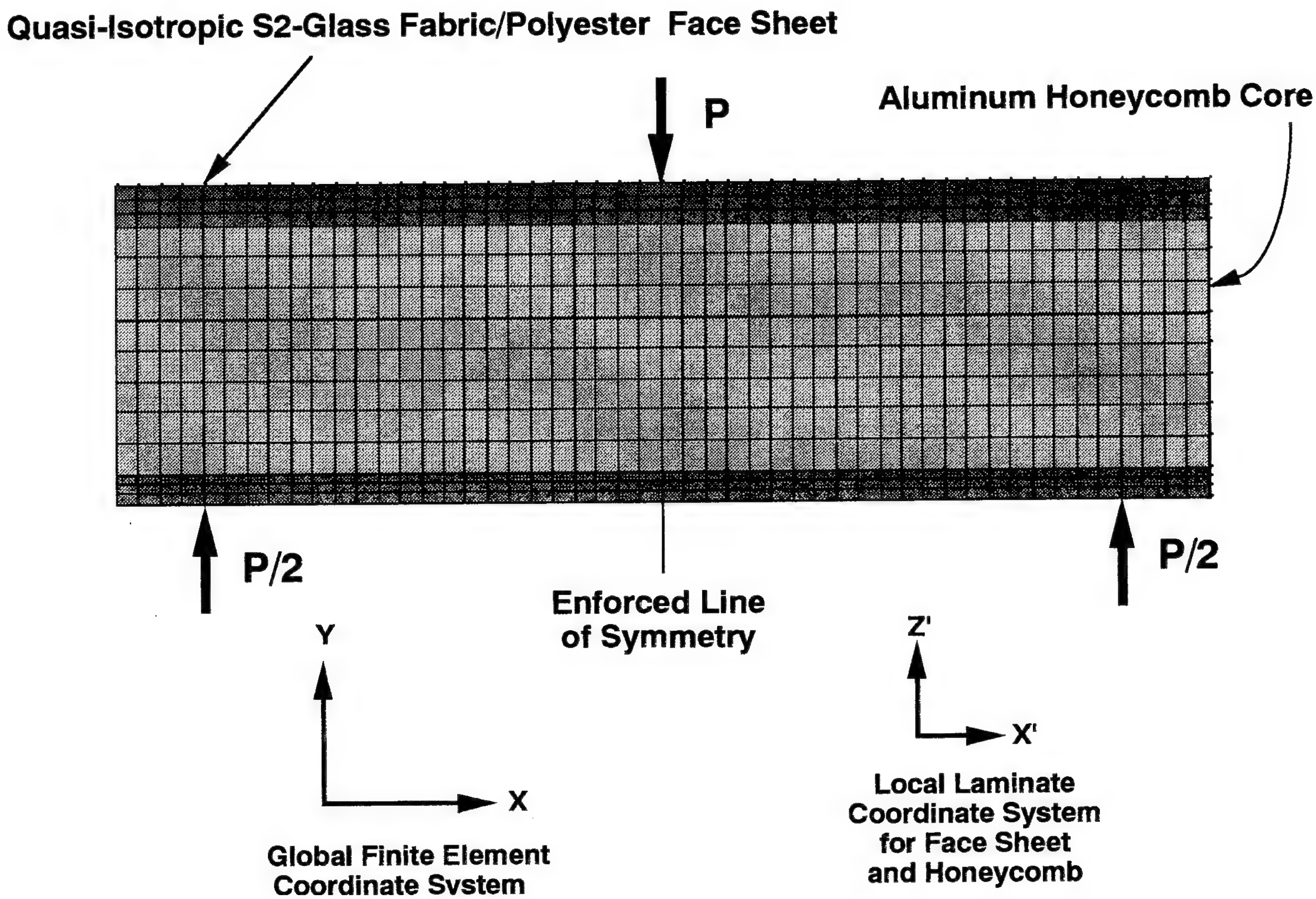

Figure 8. Finite element model of sandwich coupon loaded in three-point bending.

Table 6. Strength Allowables for the Aluminum Honeycomb Core

	Strength (MPa)	Strength (psi)
In-Plane Tensile Strength (X1T = X2T)	5.6	814.0
In-Plane Compressive Strength (X1C = X2C)	11.2	1628.0
Through-the-thickness Tensile Strength (X3T)	9.3	1345.0
Through-the-thickness Compressive Strength (X3C)	23.7	3439.0
In-Plane Shear Strength (S12)	3.1	450.0
Interlaminar Shear Strength (S13=S23)	6.2	900.0

A three-dimensional finite element model of the bending coupon was generated with the PATRAN analysis software [PDA Engineering 1990]. The finite element loading on the model was matched to a typical failure load level (P=18.2 kN) observed in mechanical tests conducted in a previous study [Condon and Gregory 1994].

NIKE3D [Maker et al. 1991] software was used to generate the stress results for the model, and LAMPAT(3.0) was then exercised in the failure assessment. Both the face sheets and the core were evaluated using the maximum stress failure criterion. The strength allowables for the face sheets and the core are given in Tables 5 and 6. The results of the LAMPAT(3.0) failure assessment are shown in Figures 9 and 10. Figure 9 shows a safety factor contour plot for the structure. Notice that the safety factor is lowest (approximately 1.1) in the center top part of the core region. Figure 10 indicates that the likely critical mode of failure in this region is MODE=6, which is through-the-thickness compressive failure (X3C). Figure 9 shows that another potential area of concern in the sandwich panel is in the areas to the left and the right of the center in the core region. Figure 10 also indicates that interlaminar (or through-the-thickness) shear (S13) failure in the aluminum core is also a potential failure mode. It is noted that both of these failure modes are consistent with the experimental tests results presented in Condon and Gregory [1994].

5. CONCLUSIONS

The major result of this work is the codification of a three-dimensional laminated media model into a computer program environment, entitled LAMPAT(3.0), for implementation as an engineering design tool for thick laminated composite structures. The theoretical basis for this program is based on the work of Chou et al. [1972]. Numerous lamina failure criteria and a

realistic laminate failure analysis methodology that employs a progressive ply failure strategy have been incorporated into the program.

LAMPAT(3.0) is user-friendly, data base-driven program, which is easily interfaced with commercially available finite element solver programs. Failure assessment results generated by the program (summarized in contour plot format) include safety factor, critical mode, and critical ply. This concise portrayal of failure within the structure significantly reduces the traditional difficulties associated with data reduction and interpretation of finite element results of thick multi-layered laminated composite structures. As a result, design changes (defined in terms of geometry, ply orientation, or material selection) can be made more routinely, facilitating the structural optimization process. LAMPAT(3.0) represents a computationally efficient tool that permits rapid, accurate analysis and design of thick section multi-layered composite structures.

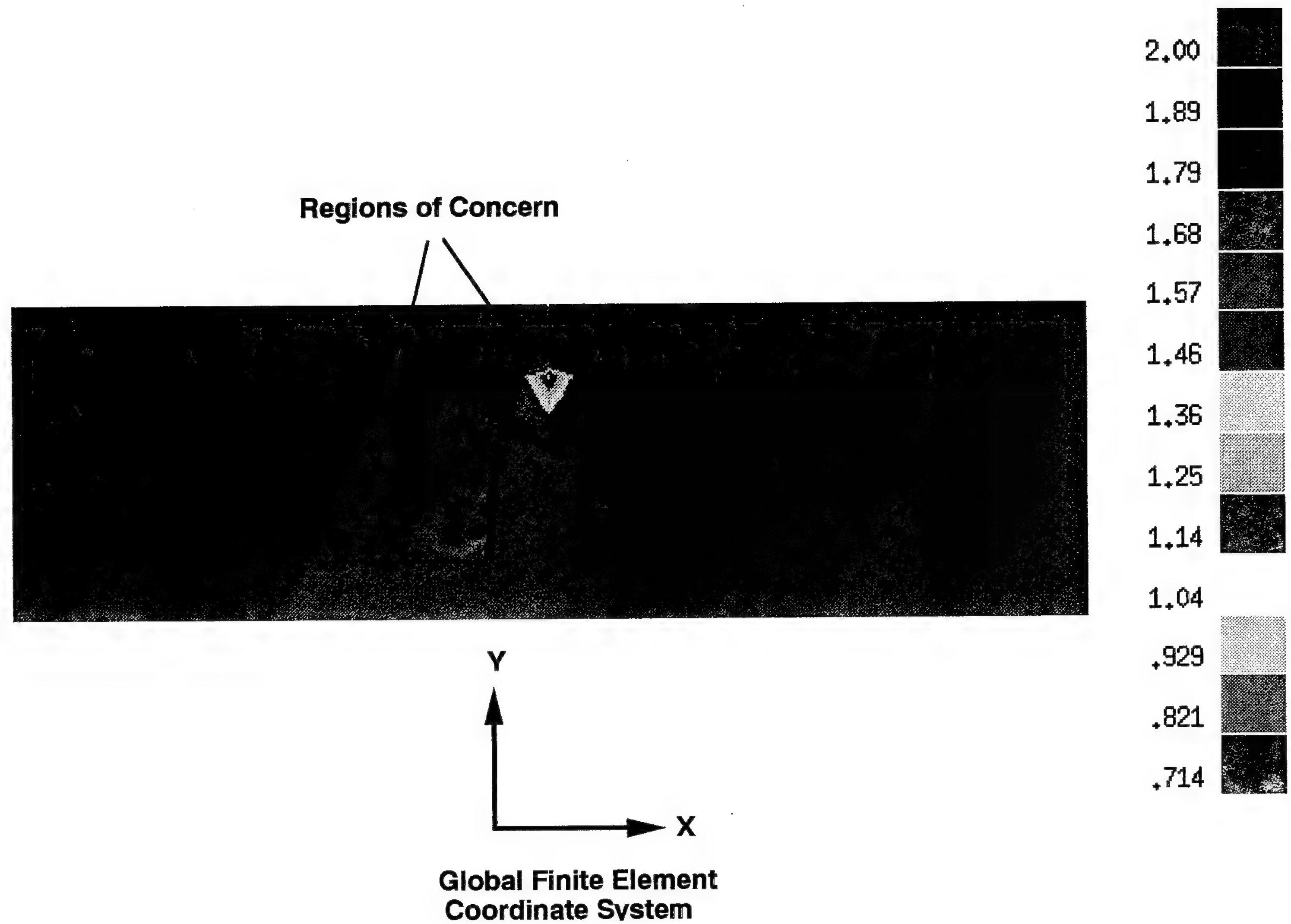

Figure 9. Safety factor contour plot.

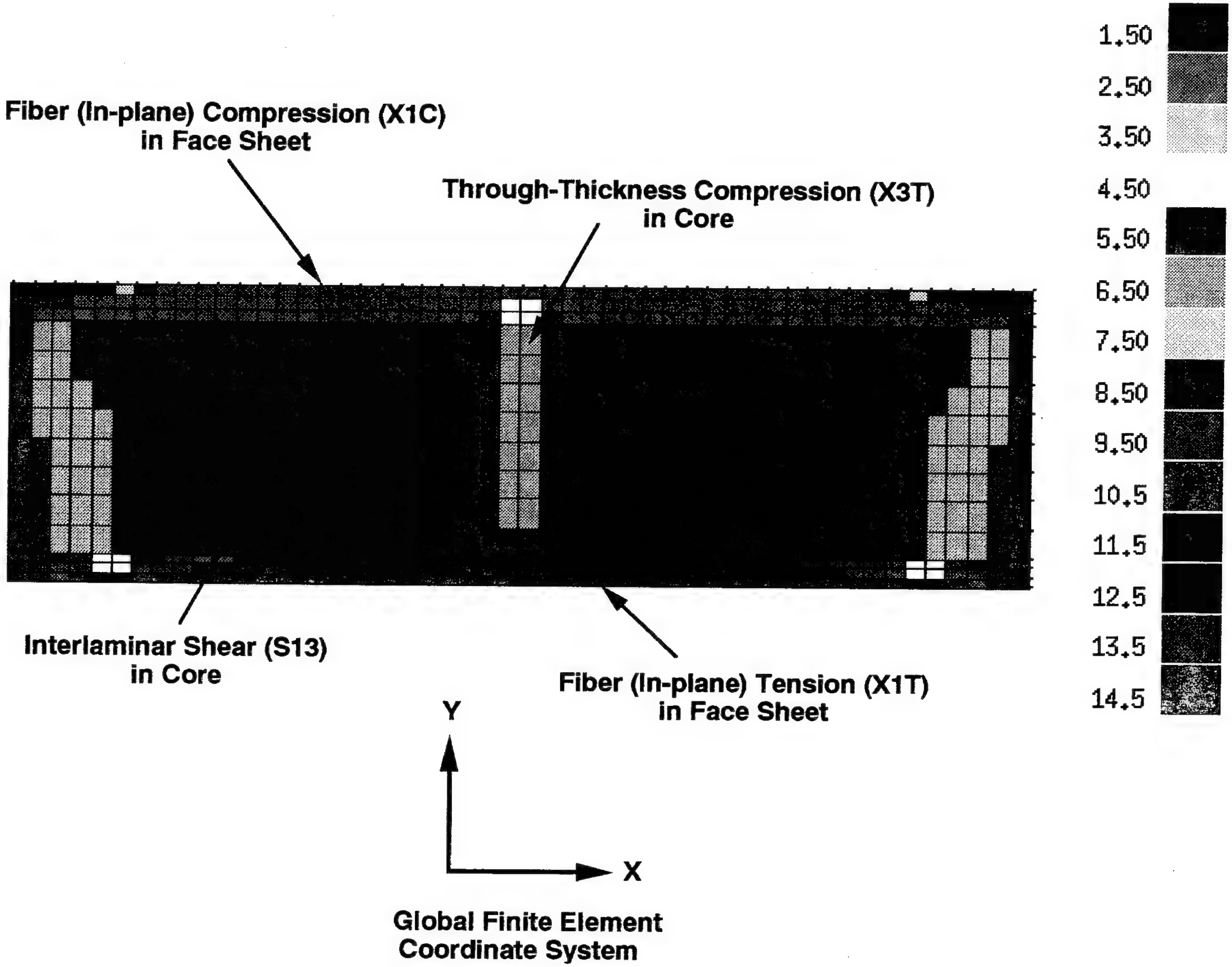

Figure 10. Critical mode identification plot.

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APPENDIX A

SAMPLE LAMPAT(3.0) MATERIAL DATA BASE

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```
2                       ! NUMBER OF REGIONS IN THE DATA BASE
3                       ! NUMBER OF MATERIALS IN DATA BASE

1.0,     2.0,     5.0,    0.0    !   REG_ID,   FAIL_CRT,   ITERS,       ---
90.0,    90.0,    0.0,    0.0    !   BETA,          PHI,   SI,          ---
4.0,     2.0,     0.0,    0.0    !   NPLY,     REG_TYP,    ---,         ---
2.0,     0.005,   0.0,   -200.0  !   MAT_#, THICKNESS, ANGLE, TEMP
2.0,     0.005,   90.0,  -200.0  !   MAT_#, THICKNESS, ANGLE, TEMP
2.0,     0.005,   90.0,  -200.0  !   MAT_#, THICKNESS, ANGLE, TEMP
2.0,     0.005,   0.0,   -200.0  !   MAT_#, THICKNESS, ANGLE, TEMP

2.0,     1.0,     5.0,    0.0    !   REG_ID,   FAIL_CRT,   ITERS, ITEXT
0.0,     0.0,     0.0,    0.0    !   BETA,          PHI,   SI,          ---
1.0,     1.0,     0.0,    0.0    !   NPLY,     REG_TYP,    ---,         ---
1.0,     0.005,   0.0,   -200.0  !   MAT_#, THICKNESS, ANGLE, TEMP

       1.0,          1.0,  0.100E+00  !   MAT_#,  MAT_TYP, MAT_DENS (Aluminum)
 10.000E+06, 10.000E+06, 10.000E+06  !     E1,        E2,        E3
  0.280E+00,  0.280E+00,  0.280E+00  !    NU23,      NU13,      NU12
  3.906E+06,  3.906E+06,  3.906E+06  !    G23,       G13,       G12
     0.0,     0.0,     0.0 !          A1,     A2,     A3
80.000E+03,   0.0,     0.0 ! (1)     VM1,    ---,     ---  (Von Mises)
     0.0,     0.0,     0.0 !         ---,    ---,     ---
     0.0,     0.0,     0.0 !         ---,    ---,     ---
     0.0,     0.0,     0.0 !         ---,    ---,     ---
     0.0,     0.0,     0.0 !         ---,    ---,     ---
     0.0,     0.0,     0.0 ! (2)     X1T,    X2T,     X3T  (Max Stress)
     0.0,     0.0,     0.0 !         X1C,    X2C,     X3C
     0.0,     0.0,     0.0 !         X23,    X13,     X12
     0.0,     0.0,     0.0 !         ---,    ---,     ---
     0.0,     0.0,     0.0 !         ---,    ---,     ---
     0.0,     0.0,     0.0 ! (3)     Y1T,    Y2T,     Y3T  (Max Strain)
     0.0,     0.0,     0.0 !         Y1C,    Y2C,     Y3C
     0.0,     0.0,     0.0 !         Y23,    Y13,     Y12
     0.0,     0.0,     0.0 !         ---,    ---,     ---
     0.0,     0.0,     0.0 !         ---,    ---,     ---
     0.0,     0.0,     0.0 ! (4)     X1T,    X2T,     HPD  (Hydro-Pressure)
     0.0,     0.0,     0.0 !      X1C(0), X2C(0),     S
     0.0,     0.0,     0.0 !         ML1,    ML2,     LTP
     0.0,     0.0,     0.0 !         MT1,    MT2,     TTP
     0.0,     0.0,     0.0 !         MS1,    MS2,     STP
     0.0,     0.0,     0.0 ! (5)     X1T,    X1C,     ---  (Tsai-Wu)
     0.0,     0.0,     0.0 !         X2T,    X2C,     ---
     0.0,     0.0,     0.0 !         S12,    F12,     F23
     0.0,     0.0,     0.0 !         ---,    ---,     ---
     0.0,     0.0,     0.0 !         ---,    ---,     ---
```

```
0.0,     0.0,     0.0  ! (6)   E1,      E2,       E3  (Christensen's)
0.0,     0.0,     0.0  !     NU23,    NU13,     NU12
0.0,     0.0,     0.0  !      G23,     G13,      G12
0.0,     0.0,     0.0  !        K,  ALPHA,       ---
0.0,     0.0,     0.0  !      Y1T,     Y1C,      ---
0.0,     0.0,     0.0  ! (7)   A1,     A11,      ---  (Feng's)
0.0,     0.0,     0.0  !       A2,      A4,      ---
0.0,     0.0,     0.0  !       A5,     A55,      ---
0.0,     0.0,     0.0  !      ---,     ---,      ---
0.0,     0.0,     0.0  !      ---,     ---,      ---
0.0,     0.0,     0.0  ! (8)  X1T,     X2T,      X3T  (Modified Hashin)
0.0,     0.0,     0.0  !      X1C,     X2C,      X3C
0.0,     0.0,     0.0  !      X23,     X13,      X12
0.0,     0.0,     0.0  !      ---,     ---,      ---
0.0,     0.0,     0.0  !      ---,     ---,      ---

  2.0,         1.0,     1.501E-04  !  MAT_#,   MAT_TYP, MAT_DENS (Graphite-Epoxy)
 2.230E+06,  1.220E+06,  1.220E+06  !     E1,         E2,         E3
 0.450E+00,  0.330E+00,  0.330E+00  !   NU23,       NU13,       NU12
 0.700E+06,  0.700E+06,  0.700E+06  !    G23,        G13,        G12
-5.000E-07,  1.550E-05,  1.550E-05  !     A1,         A2,         A3
      0.0,        0.0,        0.0  ! (1) VM1,     ---,      ---  (Von Mises)
      0.0,        0.0,        0.0  !     ---,     ---,      ---
      0.0,        0.0,        0.0  !     ---,     ---,      ---
      0.0,        0.0,        0.0  !     ---,     ---,      ---
      0.0,        0.0,        0.0  !     ---,     ---,      ---
 420.0E+03,     8.7E+03,     8.7E+03  ! (2)  X1T,   X2T,    X3T  (Max Stress)
 175.0E+03,    30.0E+03,    30.0E+03  !      X1C,   X2C,    X3C
   6.0E+03,     6.0E+03,    12.0E+03  !      X23,   X13,    X12
      0.0,        0.0,        0.0  !     ---,     ---,      ---
      0.0,        0.0,        0.0  !     ---,     ---,      ---
   0.0188,     0.0071,     0.0071  ! (3)  Y1T,   Y2T,    Y3T  (Max Strain)
   0.0078,     0.0246,     0.0246  !      Y1C,   Y2C,    Y3C
   0.0086,     0.0086,     0.0171  !      Y23,   Y13,    Y12
      0.0,        0.0,        0.0  !     ---,     ---,      ---
      0.0,        0.0,        0.0  !     ---,     ---,      ---
 420.0E+03,     8.7E+03,       1.0  ! (4)  X1T,      X2T,      HPD  (Hydro-Pressure)
 175.0E+03,   100.0E+03,  20.30E+03  !   X1C(0),  X2C(0),      S
      2.0,        2.0,        0.0  !      ML1,      ML2,      LTP
      1.0,        1.0,        0.0  !      MT1,      MT2,      TTP
      1.0,        1.0,        0.0  !      MS1,      MS2,      STP
 420.0E+03,   175.0E+03,       0.0  ! (5)  X1T,   X1C,    ---  (Tsai-Wu)
   8.7E+03,    30.0E+03,       0.0  !      X2T,   X2C,    ---
  20.0E+03, 1.1916E-09, -1.916E-09  !      S12,   F12,    F23
      0.0,        0.0,        0.0  !     ---,     ---,      ---
      0.0,        0.0,        0.0  !     ---,     ---,      ---
```

```
2.230E+06,  1.220E+06,  1.220E+06 ! (6)   E1,      E2,      E3  (Christensen's)
0.450E+00,  0.330E+00,  0.330E+00 !      NU23,    NU13,    NU12
0.700E+06,  0.700E+06,  0.700E+06 !       G23,     G13,     G12
1.507E-02,     0.1028,        0.0 !     K, ALPHA,          ---
   0.0188,     0.0078,        0.0 !       Y1T,     Y1C,     ---
   452.55,   101910.0,        0.0 ! (7)    A1,     A11,     ---  (Feng's)
   1189.1,     1189.1,        0.0 !        A2,      A4,     ---
   -37.42,    4819.74,        0.0 !        A5,     A55,     ---
      0.0,        0.0,        0.0 !       ---,     ---,     ---
      0.0,        0.0,        0.0 !       ---,     ---,     ---
420.0E+03,    8.7E+03,    8.7E+03 ! (8)   X1T,     X2T,     X3T  (Modified Hashin)
175.0E+03,   30.0E+03,   30.0E+03 !       X1C,     X2C,     X3C
 20.0E+03,   20.0E+03,   20.0E+03 !       X23,     X13,     X12
      0.0,        0.0,        0.0 !       ---,     ---,     ---
      0.0,        0.0,        0.0 !       ---,     ---,     ---

      3.0,        1.0,  1.889E-04 !  MAT_#,  MAT_TYP, MAT_DENS (S2-Glass/3501-Epoxy)
7.150E+06,  2.130E+06,  2.130E+06 !        E1,      E2,  E3
0.499E+00,  0.306E+00,  0.296E+00 !      NU23,    NU13,    NU12
0.710E+06,  0.980E+06,  0.980E+06 !       G23,     G13,     G12
2.300E-06,  1.850E-05,  1.850E-05 !        A1,      A2,  A3
      0.0,        0.0,        0.0 ! (1)   VM1,     ---,     ---  (Von Mises)
      0.0,        0.0,        0.0 !       ---,     ---,     ---
      0.0,        0.0,        0.0 !       ---,     ---,     ---
      0.0,        0.0,        0.0 !       ---,     ---,     ---
      0.0,        0.0,        0.0 !       ---,     ---,     ---
243.0E+03,    7.0E+03,    7.0E+03 ! (2)   X1T,     X2T,     X3T  (Max Stress)
177.0E+03,   30.6E+03,   35.0E+03 !       X1C,     X2C,     X3C
 15.7E+03,   17.0E+03,   15.7E+03 !       X23,     X13,     X12
      0.0,        0.0,        0.0 !       ---,     ---,     ---
      0.0,        0.0,        0.0 !       ---,     ---,     ---
   0.0340,     0.0033,     0.0040 ! (3)   Y1T,     Y2T,     Y3T  (Max Strain)
   0.0248,     0.0144,     0.0164 !       Y1C,     Y2C,     Y3C
   0.0221,     0.0174,     0.0160 !       Y23,     Y13,     Y12
      0.0,        0.0,        0.0 !       ---,     ---,     ---
      0.0,        0.0,        0.0 !       ---,     ---,     ---
      0.0,        0.0,        0.0 ! (4)   X1T,     X2T,     HPD  (Hydro-Pressure)
      0.0,        0.0,        0.0 !    X1C(0), X2C(0),      S
      0.0,        0.0,        0.0 !       ML1,     ML2,     LTP
      0.0,        0.0,        0.0 !       MT1,     MT2,     TTP
      0.0,        0.0,        0.0 !       MS1,     MS2,     STP
      0.0,        0.0,        0.0 ! (5)   X1T,     X1C,     ---  (Tsai-Wu)
      0.0,        0.0,        0.0 !       X2T,     X2C,     ---
      0.0,        0.0,        0.0 !       S12,     F12,     F23
      0.0,        0.0,        0.0 !       ---,     ---,     ---
      0.0,        0.0,        0.0 !       ---,     ---,     ---
```

```
0.0,    0.0,    0.0 ! (6)   E1,     E2,      E3  (Christensen's)
0.0,    0.0,    0.0 !       NU23,   NU13,    NU12
0.0,    0.0,    0.0 !       G23,    G13,     G12
0.0,    0.0,    0.0 !     K, ALPHA,        ---
0.0,    0.0,    0.0 !       Y1T,    Y1C,     ---
0.0,    0.0,    0.0 ! (7)   A1,     A11,     ---  (Feng's)
0.0,    0.0,    0.0 !       A2,     A4,      ---
0.0,    0.0,    0.0 !       A5,     A55,     ---
0.0,    0.0,    0.0 !       ---,    ---,     ---
0.0,    0.0,    0.0 !       ---,    ---,     ---
0.0,    0.0,    0.0 ! (8)   X1T,    X2T,     X3T  (Modified Hashin)
0.0,    0.0,    0.0 !       X1C,    X2C,     X3C
0.0,    0.0,    0.0 !       X23,    X13,     X12
0.0,    0.0,    0.0 !       ---,    ---,     ---
0.0,    0.0,    0.0 !       ---,    ---,     ---
```

APPENDIX B

TYPICAL INTERACTIVE SESSION

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B.1 Sample Pre-processing Session

```
Percent Lampat3.0

    ******************************************
    *                                        *
    *   U.S. ARMY RESEARCH LABORATORY        *
    *                                        *
    *            --- LAMPAT ---              *
    *                                        *
    *             VERSION  3.0               *
    *                                        *
    *     FEA PRE- AND POST-PROCESSOR        *
    *    FOR ISOTROPIC AND ANISOTROPIC       *
    *          LAMINATED MEDIA               *
    *                                        *
    *   LAST REVISED: 28 FEBRUARY, 1995      *
    *                                        *
    ******************************************

ENTER (1) PRE-PROCESSING -OR- (2) POST-PROCESSING >
 1

LAMPAT ELEMENT LIBRARY:
  (1) ANSYS  - AXISYMMETRIC (STIFF42)
  (2) ABAQUS - AXISYMMETRIC (CAX8R)
  (3) DYNA3D - 3D SOLID ELEMENT (HEX80)
 1

ENTER NAME OF LAMPAT INPUT FILE (DATA BASE) >
 sample.dbase

ENTER NAME OF MATERIAL CARD (PNF OR D3I)
INPUT FILE TO BE GENERATED >
 sample.card3

 LAMPAT EXECUTION COMPLETE.... PROGRAM TERMINATED.
```

B.1 Sample Post-processing Session

Percent Lampat3.0

```
*****************************************
*                                       *
*    U.S. ARMY RESEARCH LABORATORY      *
*                                       *
*            --- LAMPAT ---             *
*                                       *
*             VERSION  3.0              *
*                                       *
*     FEA PRE- AND POST-PROCESSOR       *
*    FOR ISOTROPIC AND ANISOTROPIC      *
*           LAMINATED MEDIA             *
*                                       *
*  LAST REVISED: 28 FEBRUARY, 1995      *
*                                       *
*****************************************
```

```
ENTER (1) PRE-PROCESSING -OR- (2) POST-PROCESSING >
 2

LAMPAT ELEMENT LIBRARY:
  (1) ANSYS  - AXISYMMETRIC (STIFF42)
  (2) ABAQUS - AXISYMMETRIC (CAX8R)
  (3) DYNA3D - 3D SOLID ELEMENT (HEX80)
 1

ENTER NAME OF LAMPAT INPUT FILE (DATA BASE) >
 sample.dbase

ENTER FEA MODEL FILE NAME (PNF OR D3I)
FOR INPUT >
 sample.pnf

ENTER STRESS RESULT FILE NAME
FOR INPUT >
 sample.res

ENTER LAMPAT FILE NAME
POST-PROCESSED FOR OUTPUT >
 sample.lam

 ELEMENT =>        1
 ELEMENT =>        2
```

```
.
.
.
ELEMENT =>      249
ELEMENT =>      250

LAMPAT EXECUTION COMPLETE.... PROGRAM TERMINATED
```

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